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FIRST STELLAR BINARY BLACK HOLES: STRONGEST GRAVITATIONAL WAVE BURST SOURCES

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ABSTRACT

Evolution of first population of massive metal-free binary stars is followed. Due to the low metallicity, the stars are allowed to form with large initial masses and to evolve without significant mass loss. Evolution at zero metallicity, therefore, may lead to the formation of massive remnants. In particular, black holes of intermediate-mass ($\sim 100 - 500$ M$_{\odot}$) are expected to have formed in early Universe, in contrast to the much lower mass stellar black holes (~ 10 M$_{\odot}$) being formed at present. Following a natural assumption, that some of these Population III stars have formed in binaries, the physical properties of first stellar binary black holes are presented. We find that a significant fraction of such binary black holes coalesces within the Hubble time. We point out that burst of gravitational waves from the final coalescences and the following ringdown of these binary black hole mergers can be observed in the interferometric detectors. We estimate that advanced LIGO detection rate of such mergers is at least several events per year with high signal to noise ratio ($\gtrsim 10$).

Subject headings: binaries: close — black hole physics — gravitational waves

1. INTRODUCTION

The properties of Population III stars have stirred a lot of interest in the recent years. It has been realized that zero metallicity stars with masses up to several hundred of solar masses are stable (Baraffe et al. 2001). Heger & Woosley (2002) estimated black hole (BH) masses formed in the evolution of high-mass metal-free stars. For initial masses above 40 M$_{\odot}$ the remnant is a BH with the mass essentially the same as the progenitor with the exception of stars with initial masses between 140 and 260 M$_{\odot}$ which undergo a pair instability supernova (SN) explosions and leave no remnant at all. Heger et al. (2003) found that these conclusions hold also for low, non-zero metallicity stars. Numerical studies of collapse and fragmentation of a metal free gas in the early Universe (Bromm et al. 1999, 2002; Omukai & Palla 2003) indicate that the initial mass function (IMF) of Population III stars is top heavy, and might be bimodal with the high mass peak around 100 M$_{\odot}$ (Larson 1998; Nakamura & Umemura 2001; Chabrier 2003). Every known stellar system contains a considerable fraction of binaries. Therefore it seems quite natural to allow for a possibility that some fraction of massive Population III stars formed in binaries as well, and then investigate their subsequent evolution. There is a possibility that these systems form massive black hole black hole (BH-BH) binaries which in turn may be observable in gravitational waves by the interferometric detectors.

In this paper we consider the properties of Population III binaries with the initial component masses in the range $100 - 500$ M$_{\odot}$. In § 2 we describe the model of evolution of metal-free systems leading to formation of massive BH-BH binaries. In § 3 we present characteristic properties of the BH-BH population and discuss the observability of their mergers. Conclusions and summary of results are given in § 4.

2. EVOLUTIONARY MODEL

A simple model of the evolution of Population III stars was constructed. Lacking the observational input, we used a set of recent calculations for metal-free single stars and then combined them with the basic binary evolutionary prescriptions.

Using the numerical calculations of stellar tracks for Populations III stars (Baraffe et al. 2001; Marigo et al. 2001; Schaerer 2002) we obtained the evolutionary timescale and radial expansion history of a star as a function of its initial mass. After the core hydrogen exhaustion, we calculate He-core core mass for a given star using the approximate empirical formula of Heger & Woosley (2002). Once a star has finished its nuclear evolution, we follow the work of Heger et al. (2003) to decide on core collapse outcome. Depending on the initial star mass, the low-metallicity massive star may either collapse directly and form a BH (without accompanying SN explosion) or be entirely disrupted (no remnant left) in a pair instability SN (stars within initial mass range of 140–260 M$_{\odot}$). In the former case, the total mass of collapsing star forms a BH, and we assume that there is no natal kick associated with the direct BH formation. The pulsational pair instability is also taken into account as it may remove part of the star envelope just prior to the collapse (Heger et al. 2003). We assume that half of the envelope is lost for the stars with initial mass in the range: 100-140 M$_{\odot}$.

The orbit of each binary is assumed to be circular, and the orbital separation is drawn from a distribution flat in logarithm with the maximum value of 10^6 R$_{\odot}$ (Abt 1983). Since little is known about the shape of the IMF of Population III stars we adopt a power law shape with $\alpha = -2$ exponent and draw the primary (initially more massive component) mass from such a distribution in the range of $100 - 500$ M$_{\odot}$. The secondary mass is obtained

TABLE 1
BH-BH FORMATION CHANNELS

Channel	Evolutionary Sequence[a]	Efficiency
bhbh01	BH1 BH2	0.67
bhbh02	MT1 BH1 CE2 BH2	0.15
bhbh03	MT1 BH1 MT2 BH2	0.07
bhbh04	BH1 MT2 BH2	0.05
bhbh05	all others	0.06

[a]BH1/BH2: first/second BH formation. CE: common envelope, MT: non-conservative RLOF, where 1 or 2 denotes the donor, either primary or secondary, respectively.

through mass ratio (secondary/primary) which is drawn from a flat distribution. Radial expansion of the components is followed, and in the case of Roche lobe overflow (RLOF) we apply one of the following prescriptions to calculate the outcome. For unevolved (main sequence) donors we assume that the RLOF will always lead to the component merger, thus terminating further evolution and aborting potential BH-BH formation. For evolved donors, we check whether the RLOF may lead to dynamical instability. If the donor mass is larger than twice the accretor mass ($q_{crit} = 2$), we apply standard common envelope prescription (Webbink 1984) with 100% efficiency of inspiral orbital energy conversion into the envelope ejection. Otherwise, we use the non-conservative evolution with half of the transferred material leaving the system with the angular momentum specific to a given binary (Belczynski et al. 2002). In the case of accretion, the unevolved stars are rejuvenated and may reach larger radii than their initial mass would have suggested, while the evolved stars are allowed only to increase their mass. Once a BH-BH binary is formed, the orbit decay time due to a gravitational wave emission is calculated (Peters 1964).

3. RESULTS

3.1. *Formation and Properties of BH-BH Population*

A large set ($N_{\rm tot} = 10^6$) of Population III binaries, described in the previous section, is evolved. Evolution leads to efficient formation of BH-BH systems (38%), despite the fact that significant fraction of binaries cease to exist when one of the components is disrupted in a pair instability SN (46%), or components merge in RLOF event (16%).

Major evolutionary channels along with BH-BH formation efficiencies are listed in Table 1. Most of the primordial systems form on wide orbits and never interact (channel bhbh01). Systems formed on the tight orbits interact twice, as first the primary then the secondary overfill their Roche lobes (bhbh02, bhbh03). Systems formed on the intermediate orbits interact only once; depending on the maximum component radii and the mass ratio RLOF is initiated either by the secondary (bhbh04) or the primary (within bhbh05).

In Figure 1 we present distribution of the coalescence times for the BH-BH populations. A significant fraction of BH-BH systems (0.17) coalesces within the Hubble time (15 Gyr). Binaries with short and intermediate initial periods interact and tend to either form tight BH-BH or merge in RLOF. Various subpopulations of

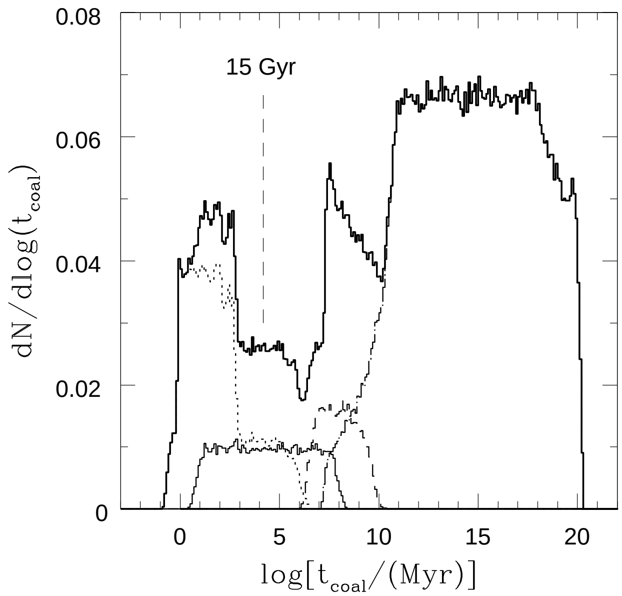

FIG. 1.— The distribution of BH-BH coalescence times (thick solid line) normalized to unity. Additionally, main subpopulations, which have evolved to BH-BH stage along different evolutionary channels, are presented with thin lines; bhbh01 long dashed dotted, bhbh02 dotted, bhbh03 solid, bhbh04 short dashed. Note that the subpopulation of systems formed along bhbh05 channels with $\log(t_{\rm coal}) \sim 3-10$ is not shown. For definition of channels see Table 1.

BH-BH systems are shown in Fig 1. The stronger (CE in case of bhbh02 as compared to non-conservative mass transfer) or more frequent interactions (two interactions in bhbh03 versus one in bhbh04) lead to shorter coalescence time of BH-BH binary. Large coalescence times are found for systems which never interacted, and basically remained on the unchanged wide orbits throughout the evolution (bhbh01). Systems with large coalescence times dominate the population, since they have formed without interactions (wide orbits) and avoided possibility of component merger in RLOF events.

Binary BHs found in our calculation cover a wide range of masses; 50–500 and 40–620 $M_\odot$ for the first and the second BH formed in a system, respectively. Total mass of BH-BH binaries spans the wide range $M = 100 - 1000\ M_\odot$, with most of the systems forming with $M = 100 - 200\ M_\odot$. The distribution of masses of the remaining population peaks at $M = 350\ M_\odot$ and has a tail extending up to $M = 1000\ M_\odot$.

3.2. *Observability in Gravitational Waves*

A coalescence of two black holes proceeds through three consecutive phases: inspiral, merger, and ringdown. The signal to noise ratio (S/N) from each phase of a coalescence in the existing and near-future interferometers has been calculated by (Flanagan & Hughes 1998). The typical total mass of a black hole binary in the population considered in this *Letter* is quite large and reaches above a few hundred $M_\odot$. The inspiral signals in interferometric detectors for such massive binaries is very low since it falls outside the maximum sensitivity range. However, the merger and ringdown signals for the advanced LIGO peak for the redshifted total masses

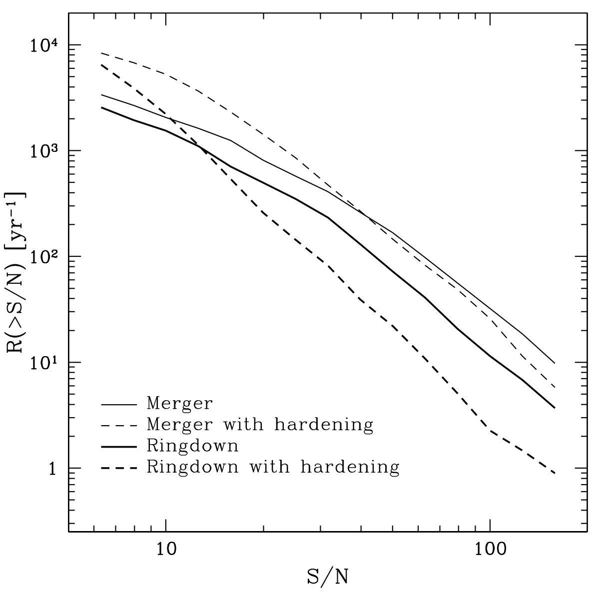

FIG. 2.— The expected observed coalescence rate of Population III BH-BH binaries as a function of signal to noise ratio for advanced LIGO detector. The thick lines correspond to detection of the ringdown signal and the thin lines to detection of the merger (burst) signal. Solid lines are for isolated orbital decay of BH-BH systems, while dashed lines represent the case when binaries are hardened in dense environment (see text for details).

between 100 and 2000 $M_\odot$.

We calculate the observed BH-BH coalescence rates following the formalism in Bulik et al. (2004), see also Bulik & Belczynski (2003). We estimate the comoving rate of Population III star formation $R_{\rm sfr}$ which would satisfy the following assumptions: *i)* formation of Population III stars occurs at a constant rate at redshifts z from 30 to 10, *ii)* $f_{\rm mass} = 10^{-3}$ of baryonic matter goes into the Population III stars (Madau & Rees 2001). We adopt a flat cosmology model with density parameter of matter $\Omega_m = 0.3$, density parameter of cosmological constant $\Omega_\Lambda = 0.7$ and for Hubble constant $H_0 = 100h\,{\rm km\ s^{-1}Mpc^{-1}}$, with $h = 0.65$. We obtain $R_{\rm sfr} \simeq 1.4\times10^{-2}{\rm M_\odot Mpc^{-3}yr^{-1}}$. Furthermore, we assume that the binary fraction in Population III stars is $f_b = 0.1$, and that the IMF below $100\,{\rm M_\odot}$ is flat, and extends down to $1{\rm M_\odot}$. We first calculate the differential merger rate as a function of redshift $df_{coal}(z)/dM$ taking into account the delay between formation and coalescence due to gravitational inspiral. The differential coalescence rate per unit observed mass is

$$\frac{dR}{dM_{obs}} = \int_0^{z_M} \frac{df_{coal}(z)}{dM}\frac{1}{1+z}\frac{dV}{dz}dz \qquad (1)$$

where $M_{obs} = M(1+z)$ is the observed (redshifted) total mass, z_M is the maximum redshift out to which a binary is observable, and dV/dz is the comoving volume element. The maximum redshift z_M is estimated using the S/N values estimated by Flanagan & Hughes (1998) for the advanced LIGO detector for merger and ringdown phases.

We present the expected rates for advanced LIGO as a function of the value of the S/N threshold as solid lines in Figure 2. The curves calculated assuming detection in merger and ringdown phases are similar because of similarity of the dependence of S/N one the masses of the system in the two cases. However, it has to be noted that the merger S/N is rather uncertain since its calculation requires precise prediction of detector noise curve as well as knowledge of highly uncertain binary parameters (e.g., BH spins). Thus the detection efficiency calculated with the use of the predicted merger S/N may be much smaller than presented in Figure 2. On the other hand the ringdown signal is much better constrained and easier to predict.

Population III BH-BH binaries might have populated dense stellar environments in young galaxies. If this was the case their coalescence times could have been significantly shortened due to the additional orbital decay by three-body interactions. We estimate the observed coalescence rates in the alternative model in which we allow for additional orbital decay due to the dynamical hardening through simple orbital shrinkage for all BH-BH binaries. Orbits are tightened by factor of 10, causing the decrease of the coalescence times by factors $\sim 10^4$. The corresponding rates are shown in Figure 2. Hardening does not have a strong impact on the observed rates because of two opposing effects. On one hand the tight binaries merge at higher redshifts and their detectability drops. On the other, the large population of wide non coalescing (for standard model, see Fig. 1) binaries is shifted to shorter coalescence times, and in particular some may add to the predicted detection rate when hardening is included.

Redshifted total mass of the system is the principal quantity that can be inferred from the observation of a ringdown signals. In Figure 3 we present the observed rate as a function of the redshifted total mass, requiring a detection with $S/N = 10$. The typical redshifted total mass lies between 600 and $1000\,{\rm M_\odot}$. In the case of the alternative model with hardening included the typical value shifts down to $\approx 300\,{\rm M_\odot}$. This is due to the fact that originally long lived binaries contain lighter black holes. A calculation using the merger signals leads to very similar results.

4. DISCUSSION

The principal result of the calculations is presented in Figure 2. The expected coalescence rate of Population III intermediate-mass BH-BH binaries is high. We predict that advanced LIGO should observe above a thousand strong ($S/N \gtrsim 10$) events per year. What are the uncertainties of this prediction?

In our calculation we have assumed that Population III stars were formed at redshifts z from 30 to 10 out of $f_{\rm mass} = 10^{-3}$ of the baryon mass contained in the Universe and that the binary fraction of the initial population was $f_b = 0.1$. The exact length and duration of the Population III star formation era does not affect the rate calculation. However, the rate scales linearly with $f_{\rm mass}$ and f_b, and although we have chosen rather conservative values for these two quantities, the rate may decrease if the adopted values were significantly lowered.

The IMF of Population III stars is another unknown. Numerical investigations show that the IMF leans towards massive stars. We assumed rather steep IMF (with the slope $\alpha = -2$), to assure that we do not overproduce highest mass, and therefore the easiest to detect, BH-BH binaries. As it turns out, the change of IMF slope

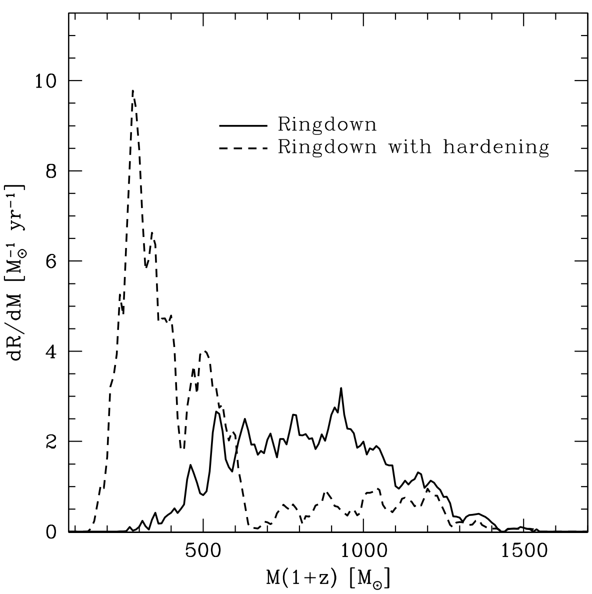

FIG. 3.— The differential rate as a function of observed (redshifted) total mass of BH-BH system. In this calculation we required a detection with high signal to noise ratio ($S/N > 10$).

does not significantly alter the detection rate. Farther steepening of the IMF ($\alpha = -3$) decreases the expected rate by half, while flatter IMF assumption ($\alpha = -1$) increases the expected rate by a factor of two. Note that we maintain a flat IMF between $1\,M_\odot$ and $100\,M_\odot$ when calculating f_{sim} – the fraction of stars that we simulate out of the total population. The observed rate scales linearly with f_{sim}. We also fixed the maximum mass of the Population III stars to $500\,M_\odot$. Had we allowed for possibility of star formation with the higher mass the rate would increase.

The estimate of the lifetime of the black hole binaries can be strongly affected if the binaries are hardened by interactions in dense stellar environments. Our simulations show that a large number of black hole binaries should be formed with the lifetimes in excess of the Hubble time. Interactions in dense systems may significantly shorten their lifetimes. We demonstrated above that hardening does not affect strongly the expected rate. Another possibility arises that the interactions disrupt some of BH-BH binaries. This would deplete the population of wide systems. None of the two effects, unless operating on extremely short timescales, can affect much systems with shortest coalescence timescales. Therefore, a combination of the two effects may constrain the mergers of Population III BH-BH binaries to large redshifts.

In order to estimate the S/N for advanced LIGO we have used the formulae of Flanagan & Hughes (1998). The predicted values of S/N may still change when more realistic noise curves and binary gravitational wave form templates are known. Because of large masses of the binaries considered in this work the changes in the low-frequency range are most important. The typical ringdown frequency is $\nu_{qnr} \approx 90(300\mathrm{M}_\odot/M)\,\mathrm{Hz}$, so the rate is most sensitive to the detector performance in the low frequency region. The scaling of the rate with the change of S/N normalization can be read off Figure 2.

The influence of the evolutionary model assumptions on detection rate was tested. We changed the CE efficiency (increase/decrease by factor of 2); altered evolution through stable RLOF phases from fully conservative to non-conservative cases; changed the specific angular momentum of the matter leaving the system during RLOF (increase/decrease by factor of 2) and varied the critical mass ratio over which the dynamical instability develops (from $q_{\rm crit} = 2$ in standard model to $q_{\rm crit} = 1 - 3$). The detection rate was decreased at most by a factor of 3 in the above models. Therefore, the predicted rate does not depend strongly on the binary evolution within the model assumptions.

Summarizing, in our calculations we have tried to use rather conservative assumptions in order not to overestimate the detection rate of Population III BH-BH mergers. If several of the assumptions and values of the model parameters are changed within reasonable limits, we still obtain a significant detection rate. Even if the rate predicted for our already conservative model is decreased by 2-3 orders of magnitude to allow for different aforementioned uncertainties, we still are left with several strong events per year for advanced LIGO detector. For initial LIGO phase the detection rate falls below one event per year.

We have shown that Population III stars may lead to formation of a large number of binaries containing intermediate-mass black holes. A significant fraction of such systems has coalescence times smaller than the Hubble time. Coalescences of intermediate-mass BH-BH binaries should be detectable by advanced interferometric gravitational wave detectors during the ringdown phase, and possibly also merger phase, provided that accurate templates are available. Given the large expected rate of observed coalescences such events could be the primary targets for LIGO burst search.

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